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High-frequency modeling of GaN/SiC blue light-emitting diodes

P. Antoranz,[a] J. M. Miranda, and J. L. Sebastián
Departamento Física Aplicada III, Universidad Complutense de Madrid, 28040 Madrid, Spain

M. Cámara and V. Fonseca
Departamento Física Atómica, Molecular y Nuclear, Universidad Complutense de Madrid, 28040 Madrid, Spain

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We report on this work a model to accurately predict the electrical behavior of double-heterostructure GaN/SiC blue light-emitting diodes up to microwave frequencies. A procedure to extract the series resistance (R_s) from the reflection coefficient is suggested. This procedure offers the advantage of using measurements without any bias current and therefore the obtained values of R_s are influenced neither by the device heating nor by inaccuracies in the calculation of the ideality factor. The junction capacitance and conductance measured in the range 1 kHz–10 MHz shows two different relaxation mechanisms, and the total capacitance can be fitted very accurately to a double Lorentzian function. Blue light-emitting diodes and lasers based on gallium nitride (GaN) semiconductor compounds represent one of the most important breakthroughs in electronics and optoelectronics of recent years. The combination of silicon carbide (SiC) and GaN has recently enabled low-cost blue-emitting diodes to be introduced in industry. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1877813]

Most of the research work published up to today in GaN/SiC devices has been addressed to improvements in different steps of the fabrication process, such as GaN doping,[1] characterization of interfacial defects,[2] dc and low-frequency electrical characterization,[3,4] or efficiency optimization.[5] However, we believe that the high-frequency behavior of blue light-emitting diodes (LEDs) has not been investigated in detail yet. The validation of a high-frequency LED model demands for a good technology that is able to supply repeatable and well-behaved devices, and now this technology is available. The performance of blue LEDs excited by high-speed signals is not only of interest for communication engineering but also relevant in the development of fast light pulse generators, which encounter a number of applications in science and other branches of engineering.

With these motivations in mind, we present here a circuital model based on physically meaningful elements that is able to accurately reproduce the electrical behavior of GaN/SiC blue LEDs in a fairly wide range of frequencies. The model takes into account the parasitic effects of package and bonding wires, the series resistance, and the nonlinear behavior of the junction capacitance and conductance. It has been verified experimentally at frequencies up to 2 GHz. The extraction of the equivalent circuit elements that reproduce the parasitic effects has enabled us to clearly identify what is the limiting factor that affects the high-frequency behavior of the device, and what are the maximum frequencies at which the device impedance is dominated by the intrinsic behavior of their characteristic elements rather than by parasitics. This information cannot be obtained from conventional $I-V$ or low-frequency (<10 MHz) $C-V$ measurements.

Figure 1 shows the equivalent circuit used to simulate the device. It includes two parasitic elements, C_p and L_p, which simulate the capacitance of the device package and the inductance of the bonding wires, respectively. The other three elements are well known and account for the intrinsic behavior of the LED. The small section of the transmission line simulates the coaxial subminiature A (SMA) connector where the devices are mounted.

The series resistance has two main contributions, one is nearly constant and is located at the ohmic contacts and the second contribution accounts for the neutral part of the diodes and depends, in principle, on the bias. However, this dependence is usually negligible. The series resistance is typically extracted from the $I-V$ curve by solving in a self-consistent way the diode equation,

$$I = I_0 e^{\frac{q(V-R_s I)}{\eta kT}}, \quad (1)$$

where the ideality factor η depends on the dominant conduction mechanism. This procedure has limitations when applied to a number of devices including LEDs, which are derived from the fact that neither η nor T is really constant. We have adopted here a different approach in which R_s is extracted by

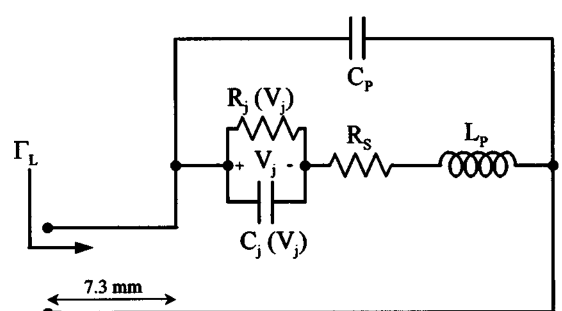

FIG. 1. Equivalent circuit of the LED.

[a]Electronic mail: pedro_antoranz@ya.com

optimization from the reflection coefficient measurements at high frequencies. The measurement is made at 0 V. The high sensitivity of the reflection coefficient to the series resistance is derived from the fact that at high frequencies the junction resistance is almost "short circuited" by the junction capacitance. This enables an accurate extraction of R_s without any error derived from the device heating or from inaccuracies in the estimation of the ideality factor.

When a generator of impedance Z_0 feeds the LED with a high-frequency small ac signal, a reflected voltage emerges from the device due to the impedance mismatch. The measured reflection coefficient Γ_L at the calibration reference plane is related to the LED impedance Z_L through the following expression:

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} e^{-2j\omega\sqrt{\mu_0\varepsilon}\ell}, \tag{2}$$

where ε is the dielectric permittivity of the Teflon and l the SMA connector length, which is 7.3 mm in our samples.

The measurement of Γ_L can be made with a network analyzer having the standard characteristic impedance of $Z_0 = 50\ \Omega$ in a fairly wide range of frequencies.

As shown in Fig. 1, the device model consists of five different elements. Therefore, a single optimization of all the elements to fit the reflection coefficient measurement to the simulation at all the frequencies is neither effective nor able to provide physically sound values. However, the fairly broad band of the network analyzer enables one to measure the LED impedance Z_L even at frequencies where this impedance is dominated by parasitics. This makes it possible to separately extract C_P and L_p by optimization at the highest frequencies. Accurate initial values for C_j and R_j are obtained from conventional $G-V$ and $C-V$ measurements at 10 MHz, and finally R_s can be obtained by optimizing it together with a slight tuning of C_j and R_j to fit the measured reflection coefficient to the simulation at the lowest frequencies measured by the network analyzer. The identification of the "high-" and "low-frequency" bands of measurement for the optimization can easily be guessed by inspection of the bias dependence of the reflection coefficient.

In order to illustrate the accuracy of the proposed model, we have tested a SiC/GaN double-heterostructure blue LED mounted in a standard T-1 3/4 lamp.[6] The device has a vertical structure with a *p-n* junction effective area of $240 \times 240\ \mu$m, and features a radiant flux of $1150\ \mu$W at 20 mA. Other references provide additional details on the device structure[7] and emission spectra.[8] The measured and simulated reflection coefficients for bias voltages of 0 and 4.5 V are shown in the Smith chart of Fig. 2. As can be seen, theoretical and experimental curves can hardly be distinguished at any of the bias points, and the final values obtained for the parasitic elements are fairly not dependent on the bias. In addition, the values for C_p, rather small in comparison with other rf diodes, and L_p, relatively large, are in good agreement with the physical structure of the chip mount, which features a significantly long bonding wire at the anode and low capacitive effects between the anode and cathode contacts.

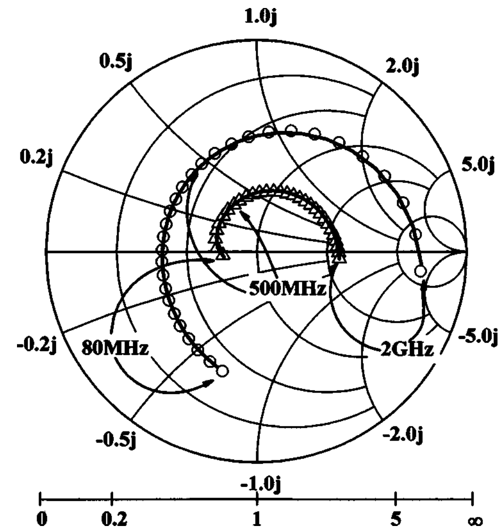

FIG. 2. Measured (symbols) and simulated (lines) reflection coefficients of the diode in equilibrium (circles) and with a forward bias of 4.5 V (triangles). $|\Gamma_L|$ for 4.5 V has been divided by three in order to differentiate the curves better. The values of the elements used in the simulation are $R_j = 1371\ \Omega$, $C_j = 54.92$ pF, $R_s = 19\ \Omega$, $C_p = 0.3$ pF, and $L_p = 6.5$ nH (equilibrium), and $R_j = 11.54\ \Omega$, $C_j = 145$ pF, $R_s = 19\ \Omega$, $C_p = 0.3$ pF, and $L_p = 6.5$ nH (bias of 4.5 V).

The parasitic elements C_p and L_p were extracted by optimization of the reflection coefficient from 500 MHz to 2 GHz. The gradient algorithm[9] was used, and the results were confirmed by repeating the optimization with two additional numerical routines, based on the MinMax and NelderMead techniques.[10,11] As it can be seen in Fig. 2, the impedance in this range is nearly insensitive to the bias, and therefore is dominated by parasitics. This fact was confirmed by the strong variation of the reflection coefficient observed when either of the two elements were "manually" tuned while keeping constant the other three elements of the model.

Initial values for the optimization of R_j and C_j were obtained from the differential impedance measured at 1 MHz. Then R_s, C_j, and R_j were optimized in the full range of frequencies at which the reflection coefficient was measured.

An ideality factor of $\eta = 8.5$ was estimated by following the conventional procedure based on the $I-V$ curves. This factor was calculated after estimating the series resistance from the reflection coefficient measurements and extracting the corresponding voltage drop from the total measured voltage. In order to minimize the effects of the device heating on the calculation, only the lowest current points that fit well to the diode equation were used. The anomalously high value obtained for η agrees well with the reports made by other authors in the characterization of similar devices.[12]

Two different arguments have been defended to explain ideality factors above 2 in these devices, the existence of multiple junctions inside the device[12] and the presence of deep-level-assisted tunneling effects.[13–15]

Figure 3 shows the differential admittance of the LED, as measured with a HP 4192A impedance analyzer, the junction capacitance and resistance measured at rf and micro-

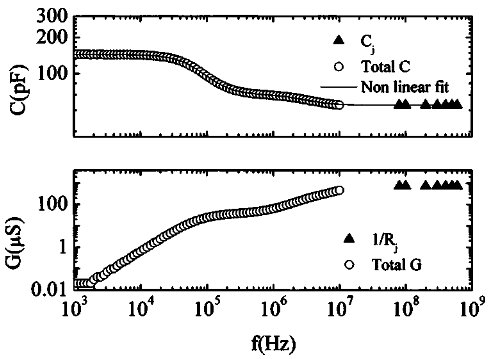

FIG. 3. C-f and G-f curves at 0 V. Total low-frequency conductance and capacitance (open circles) and high-frequency junction conductance and capacitance (triangles). The nonlinear fit shown in the capacitance plot was obtained with $C_1=77.5$ pF, $\tau_1=2.08$ μs, $C_2=12$ pF, $\tau_2=54.9$ ns, and $C_j=54.92$ pF.

wave frequencies, and a no linear fit to the measured capacitance for the full range of frequencies. This fit was achieved with the following model:

$$C = C_j + \frac{C_1}{1+(\omega\tau_1)^2} + \frac{C_2}{1+(\omega\tau_2)^2}. \qquad (3)$$

The presence of several junctions in the device is consistent with the observed dependence of the measured conductance on the frequency below 10 MHz. Although a single frequency-dependent junction conductance and capacitance would explain the measurements as well, the authors are not aware of any tunneling effects with time constants as high as the ones observed here.

It must be pointed out that the three contributions to the frequency-dependent capacitance measured here are additive and therefore cannot account for three different capacitances located in different parts of the device and connected in series. Therefore, the Lorentzian dependence of the capacitance is an attribute that must be assigned to the full device rather than to individual parts of it. Nevertheless, the high accuracy of the model given by Fig. 1 demonstrates that multiple junctions need only be considered below 10 MHz.

It is worth mentioning the following concluding remarks: (1) The measured anomalously high value of the ideality factor in the double-heterostructure (DH) SiC/GaN blue LED presented in this work confirms previously reported work in similar structures. (2) The model proposed here to predict the high-frequency behavior of DH SiC/GaN blue LEDs is able to accurately estimate the device impedance even at frequencies at which this impedance is fully dominated by parasitics. The parasitic inductance of the bonding wire has been identified as the main limiting factor in the high-frequency behavior of the device. (3) The admittance measured up to 10 MHz is consistent with the high-frequency model presented in this work, by assuming a nonlinear Lorentzian behavior of the device capacitance with two different time constants. (4) The frequency dependence of the conductance measured below 10 MHz could be explained by the presence of multiple rectifying junctions, but at higher frequencies a single junction model is accurate enough. (5) The high sensitivity of the reflection coefficient at 0 V to the series resistance enables the calculation of this factor without any errors derived from the device heating or from the inaccuracies in the estimation of the ideality factor.

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